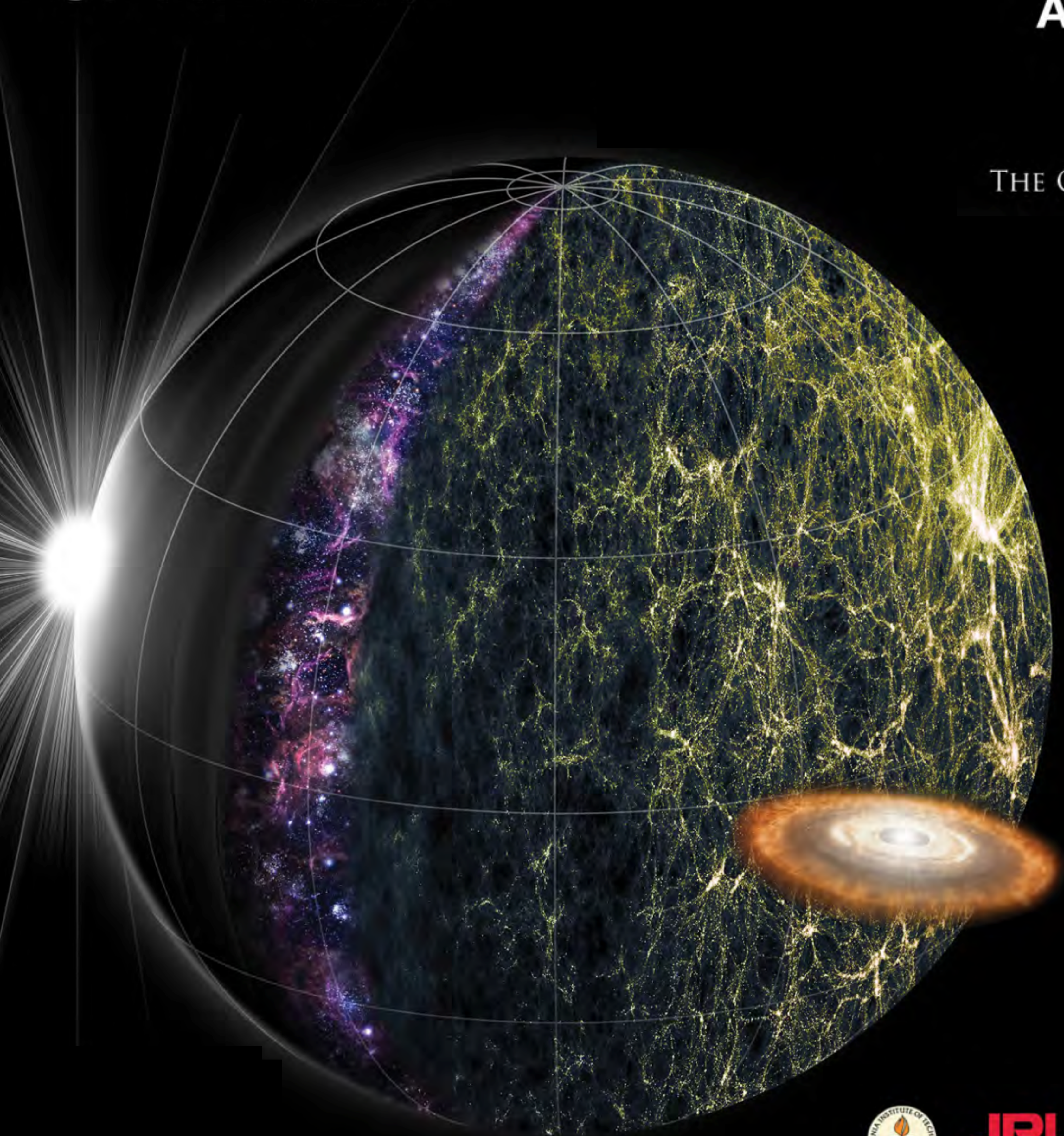
SPHEREx

An All-Sky Spectral Survey

DESIGNED TO EXPLORE:
THE ORIGIN OF THE UNIVERSE
THE ORIGIN AND HISTORY OF GALAXIES
THE ORIGIN OF WATER IN PLANETARY SYSTEMS



Olivier Doré
JPL/Caltech

for the SPHEREx team

http://spherex.caltech.edu

SPHEREx: An All-Sky Spectral Survey

Spectro-Photometer for the History of the Universe, Epoch of Reionization, and Ices Explorer

A high throughput, low-resolution near-infrared spectrometer.

SPHEREx Dataset:

For *every* 6.2” pixel over the entire sky:

➡ R=40 spectra spanning (0.75 μm < λ < 4.81 μm).
➡ R=150 spectra (4.1 μm < λ < 4.8 μm).

O.D., Bock et al., arXiv:1412.4872

Three Major Scientific Themes

- Inflation Investigation:
  - ➡ Cosmology with the 3D clustering of galaxies.
    - Survey the $z<1.5$ Universe to fundamental limits to measure signatures of inflation (non-Gaussianity, primordial power spectrum shape) and dark energy.
    - Complement Euclid and WFIRST which survey smaller area at $z>1$.

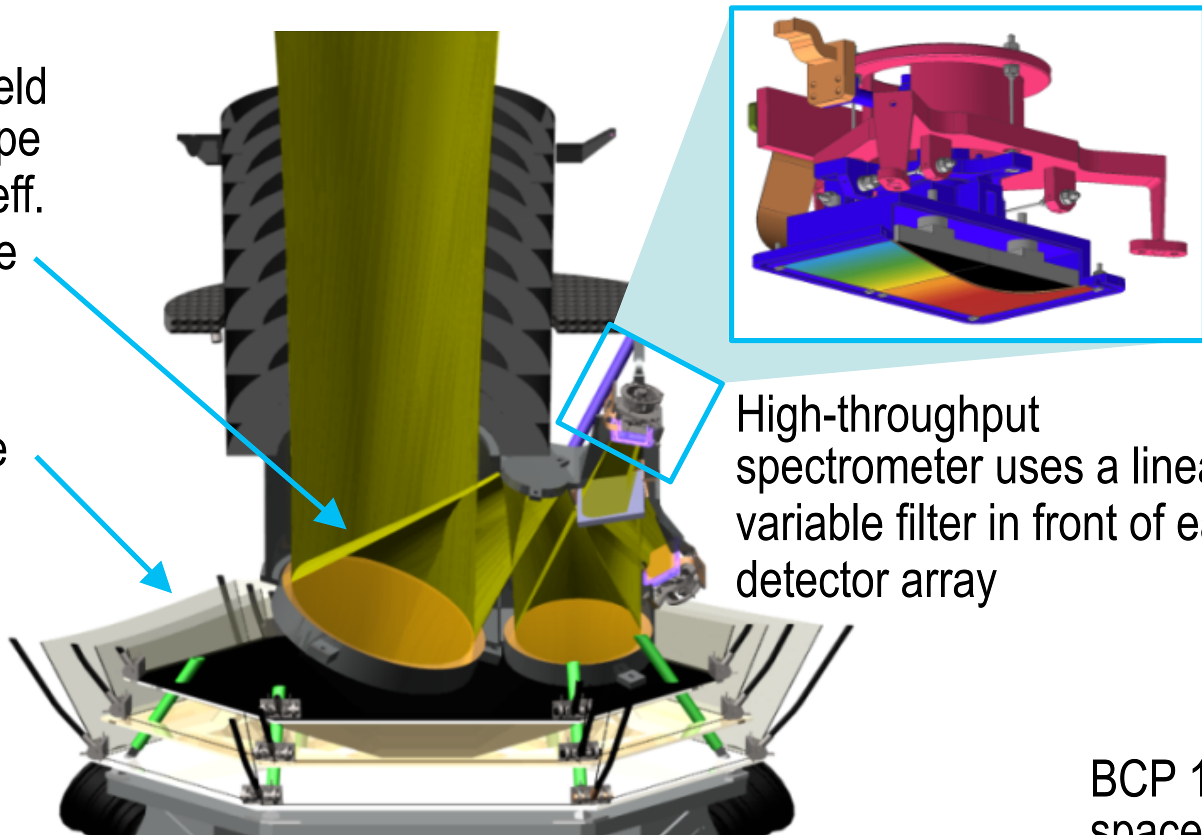
- Galaxy Evolution Investigation:
  - ➡ Measure the extra-galactic background light (EBL) to probe the epoch of reionization (EOR).

- Ice Investigation:
  - ➡ Measure how interstellar ices bring water and organic molecules into proto-planetary systems through broad absorption features in stellar spectra.

A Simple Instrument with Large Margins

Wide-field
(TMA) telescope
20 cm eff.
aperture

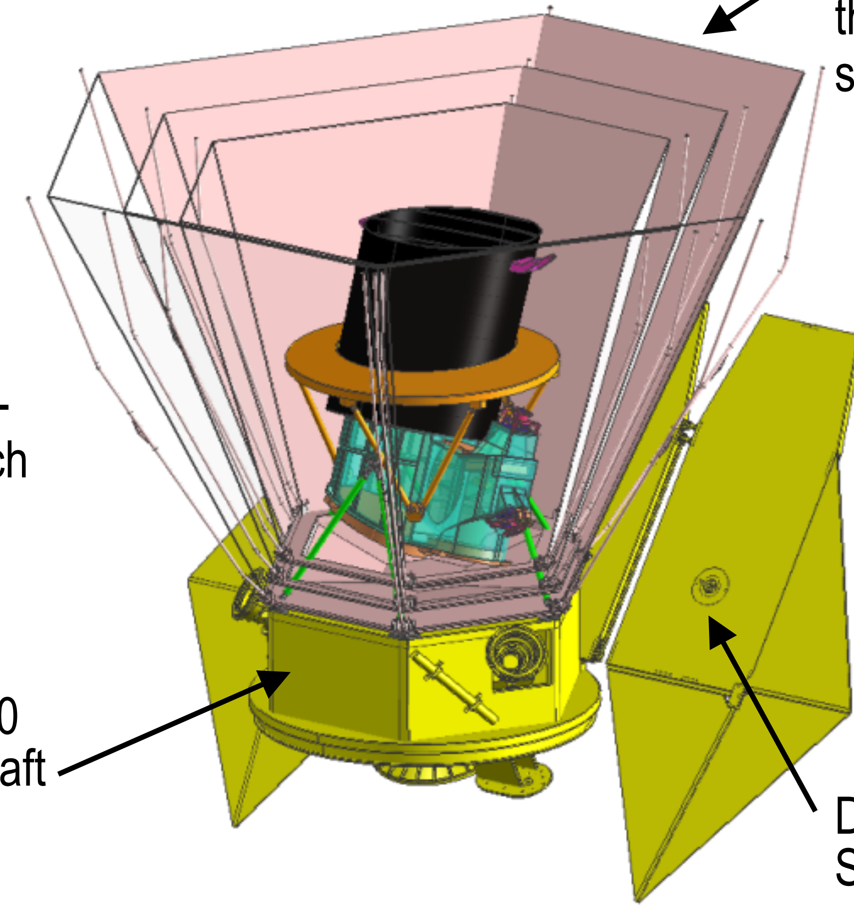
Passive
cooling
system



High-throughput spectrometer uses a linear-variable filter in front of each detector array

SPHEREx has uniquely large spectral light-collecting power for mapping the entire sky

Deployed
thermal
shields



185 cm

BCP 100
spacecraft

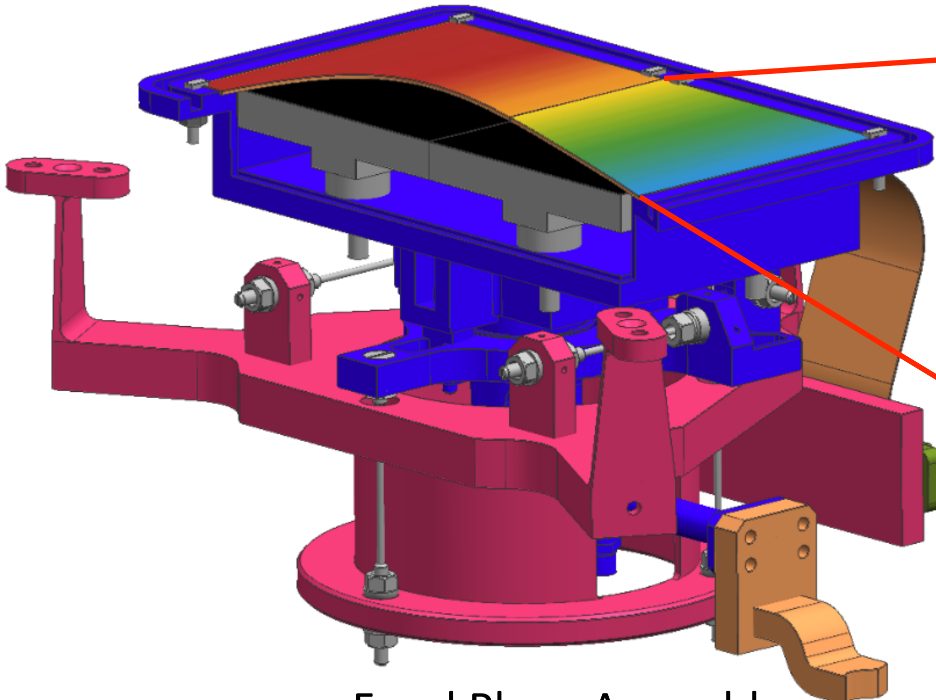
Deployed
Solar
panels

Instrument & Mission Parameters

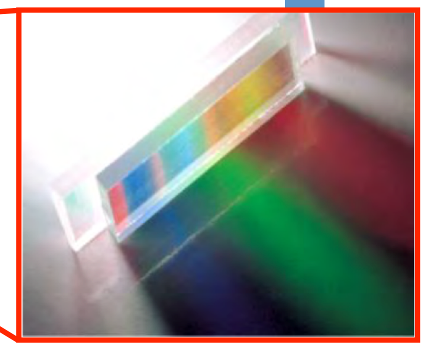
Parameter	Value
Telescope Effective Aperture	20 cm
Pixel Size	6.2" x 6.2"
Field of View	2 x (3.5º x 7.0º); dichroic
Spectrometer	Linear-Variable Filters
Resolving Power and Wavelength Coverage	R=41.5 λ=0.75 - 4.1 μm R=150 λ=4.1 - 4.8 μm
Arrays	2 x Hawaii-2RG 2.5 μm 2 x Hawaii-2RG 5.3 μm
Point Source Sensitivity (MEV Performance)	18.5 AB mag (5σ) with 300% margin to req't
Cooling	All-Passive
2.5 μm Array and Optics Temperature	80 K with 700% margin on total heat load
5.3 μm Array Temperature	55 K with 450% margin on total heat load
Payload Mass	68.1 kg (CBE+31% Ctg)
Payload Power	27.8 W (CBE+30% Ctg)

Parameter	Performance	Margin
Spacecraft	Ball BCP 100	N/A
Science Data Downlink	73 Gb/day	97%
Pointing Stability	2.1" (1σ) over 200 s	43%
Pointing Control	22.7" (1σ)	164%
Pointing Agility	70º in 116 s (large slews) 8.8' in 6 s (small steps)	29% 233%
Observatory Mass	173.6 kg (MEV)	53%
Observatory Power	171.8 W (MEV)	36%
Solar Array Power Output (EOL)	234 W	N/A

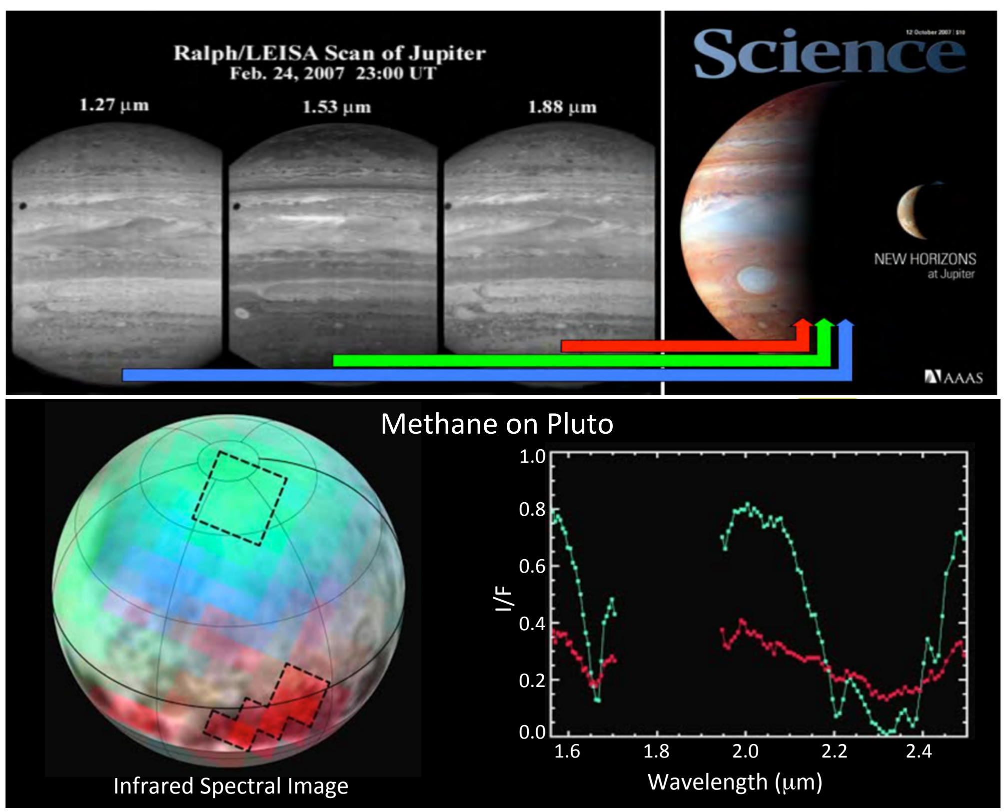
High-Throughput LVF Spectrometer



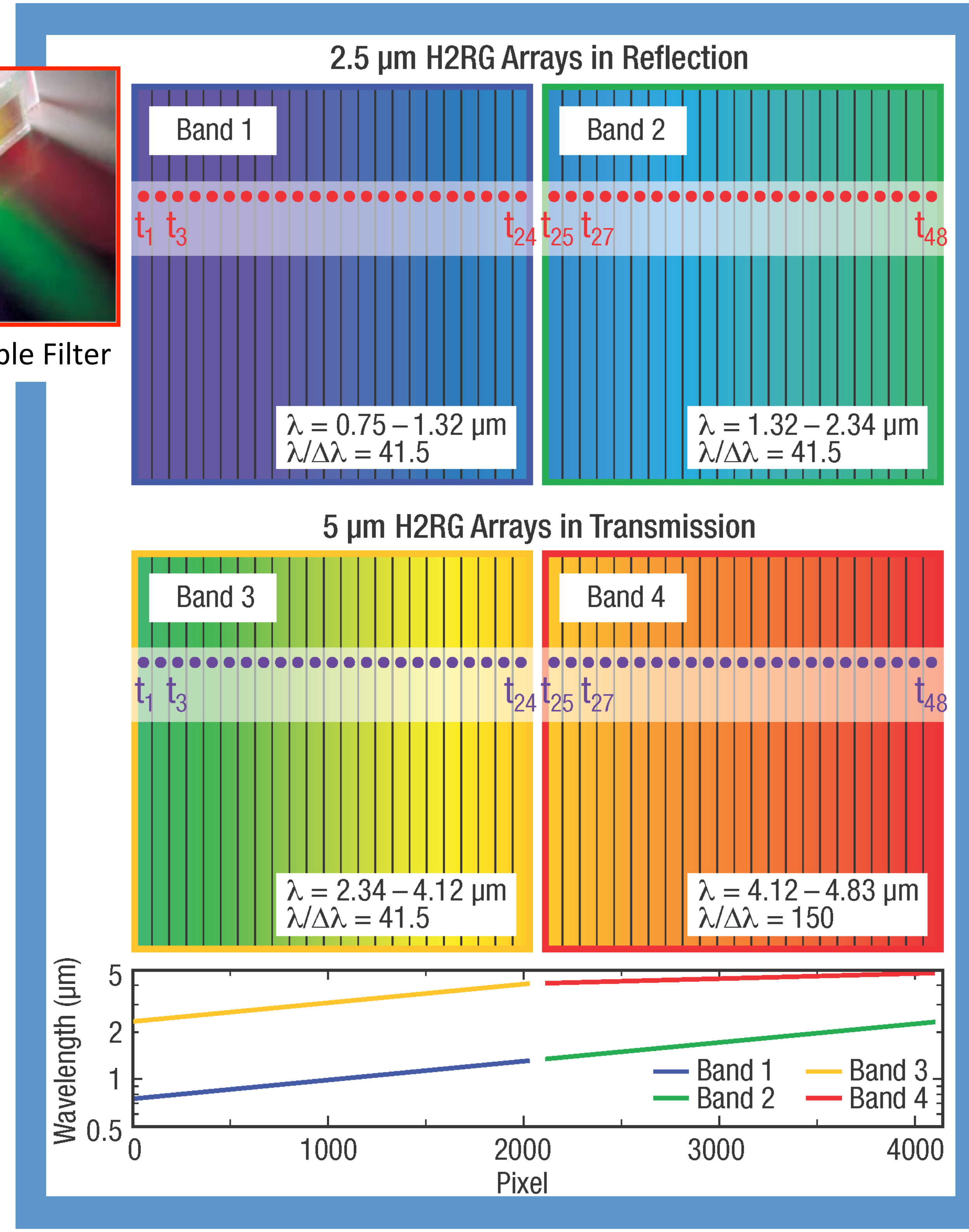
Focal Plane Assembly



Linear Variable Filter



LVFs used on ISOCAM, HST-WFPC2,
New Horizons LEISA, & OSIRIX-Rex (2016 launch)



Spectra obtained by stepping source over the FOV in multiple images: **no moving parts**

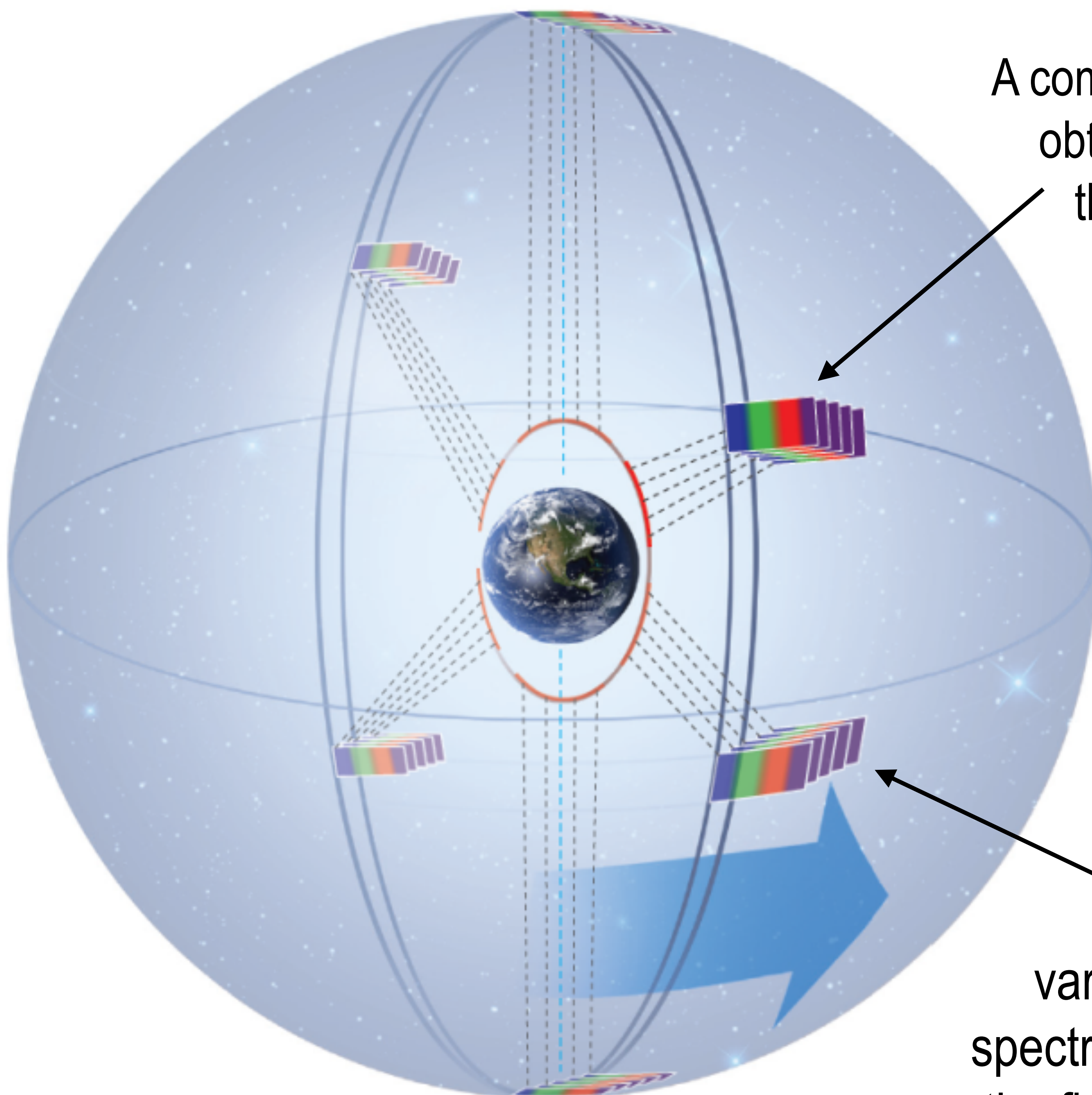
An Efficient All-Sky Survey in a Step and Repeat Fashion

SPHEREx maps the entire sky with one simple observing mode:

➡ The spacecraft steps and points the wide-field telescope,tiling the sky every 6 months.

➡Multiple images produce complete spectra over the full sky.

➡The sun-synchronous LEO orbits enable simple passive cooling for NIR detectors.



Very efficient survey: 85% of the time is dedicated to science

Spangelo et al., arXiv:1412.3142

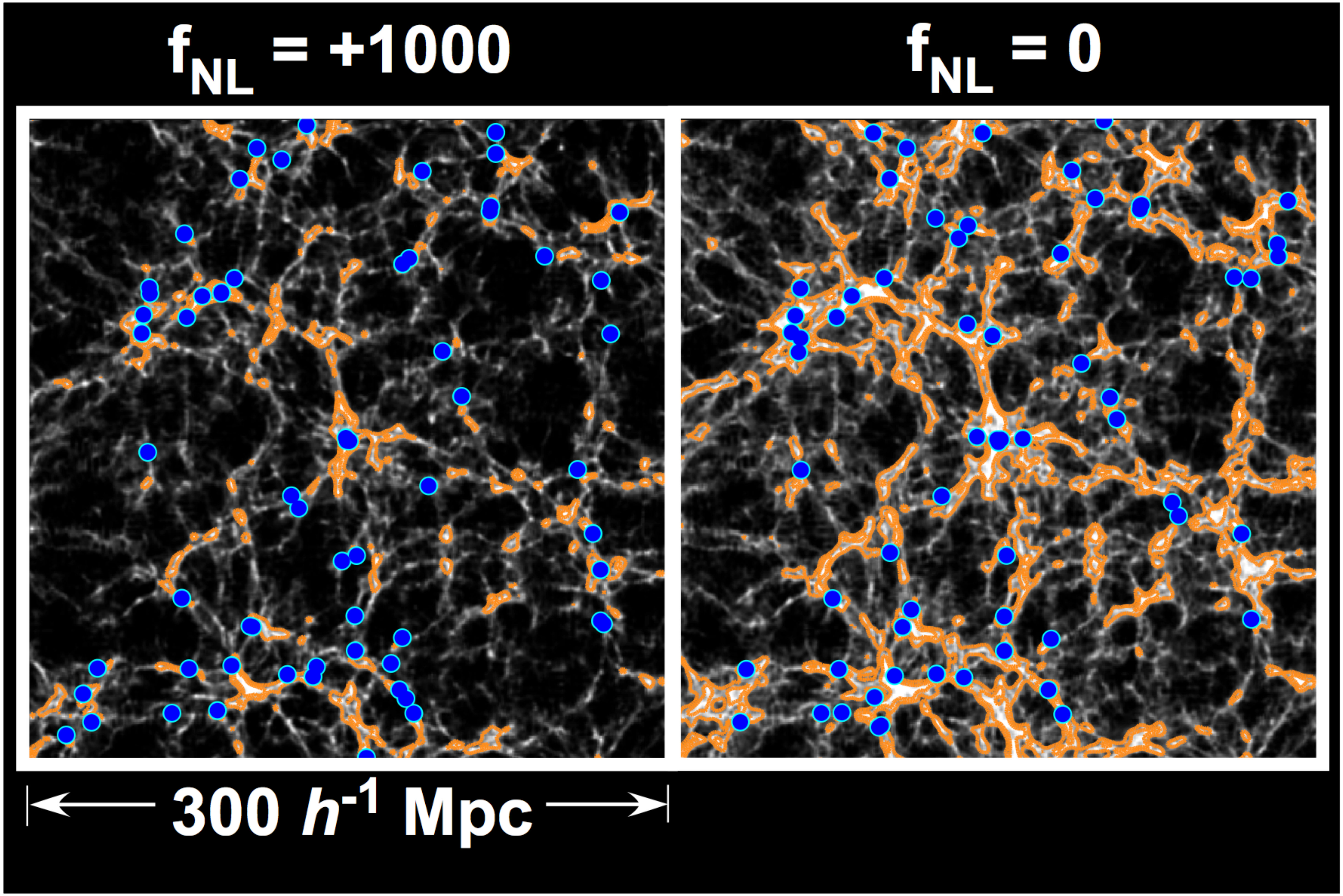
SPHEREx Team

Jamie Bock (PI)	Caltech/JPL
Matt Ashby	CfA
Peter Capak	IPAC
Asantha Cooray	UC Irvine
Olivier Doré (PS)	JPL/Caltech
Chris Hirata	OSU
Woong-Seob Jeong	KASI
Phil Korngut	Caltech
Dae-Hee Lee	KASI
Gary Melnick	CfA
Roger Smith	Caltech
Yong-Seon Song	KASI
Stephen Unwin	JPL
Michael Werner	JPL
Michael Zemcov	Caltech

Roland de Putter	JPL
Tim Eifler	JPL
Nicolas Flagey	IfA
Yan Gong	UC Irvine
Elisabeth Krause	Stanford
Daniel Masters	Caltech
Phil Mauskopf	ASU
Bertrand Menneson	JPL
Hien Nguyen	JPL
Karin Öberg	CfA
Anthony Pullen	CMU
Alvise Raccanelli	JHU
Volker Tolls	CfA
Salman Habib	Argonne
Katrin Heitmann	Argonne
Marco Viero	Stanford

Inflation Investigation

Primordial Non-Gaussianity affects Galaxy Clustering - I



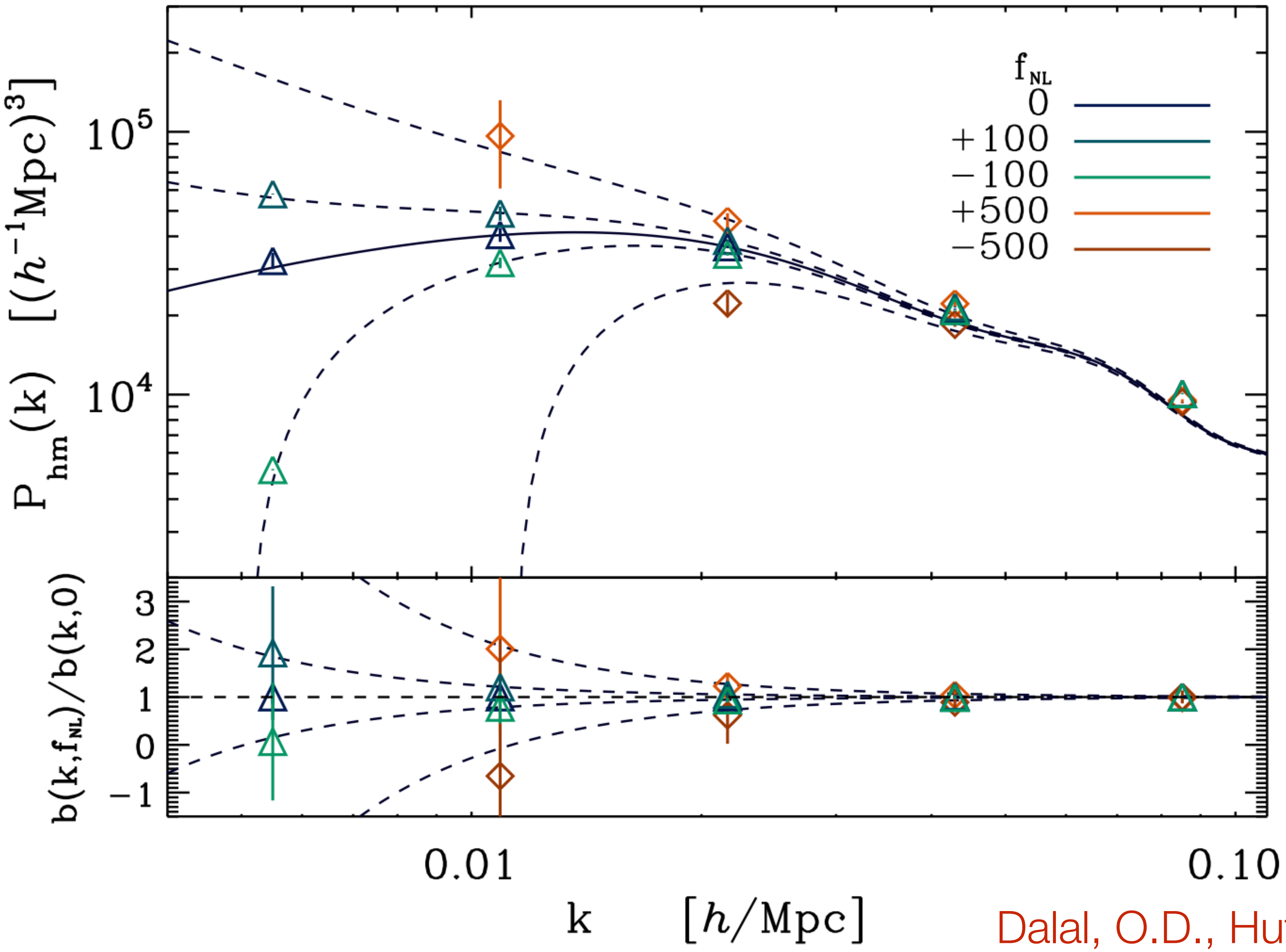
Why Studying primordial non-Gaussianity?

	$f_{\rm NL}^{\rm loc} \lesssim 1$	$f_{\rm NL}^{\rm loc} \gtrsim 1$
$f_{\rm NL}^{\rm eq,\,orth} \lesssim 1$	Single-field slow-roll	Multi-field
$f_{\rm NL}^{\rm eq,\,orth} \gtrsim 1$	Single-field non-slow-roll	Multi-field

- Well-defined theory targets exist.
- Planck tells us $f_{NL} \lesssim 5$ (68% C.L.).
- The polarized CMB cosmic variance limit is about $\lesssim 3$ (68% C.L.)
  - ➡ Large-scale structure (3D mapping) measurements are needed.

Testing Inflation with Large Scale Structure: Connecting Hopes with Reality (conveners: O.D., D. Green, Alvarez et al., arXiv:1412.4671)

Primordial Non-Gaussianity affects Galaxy Clustering - II

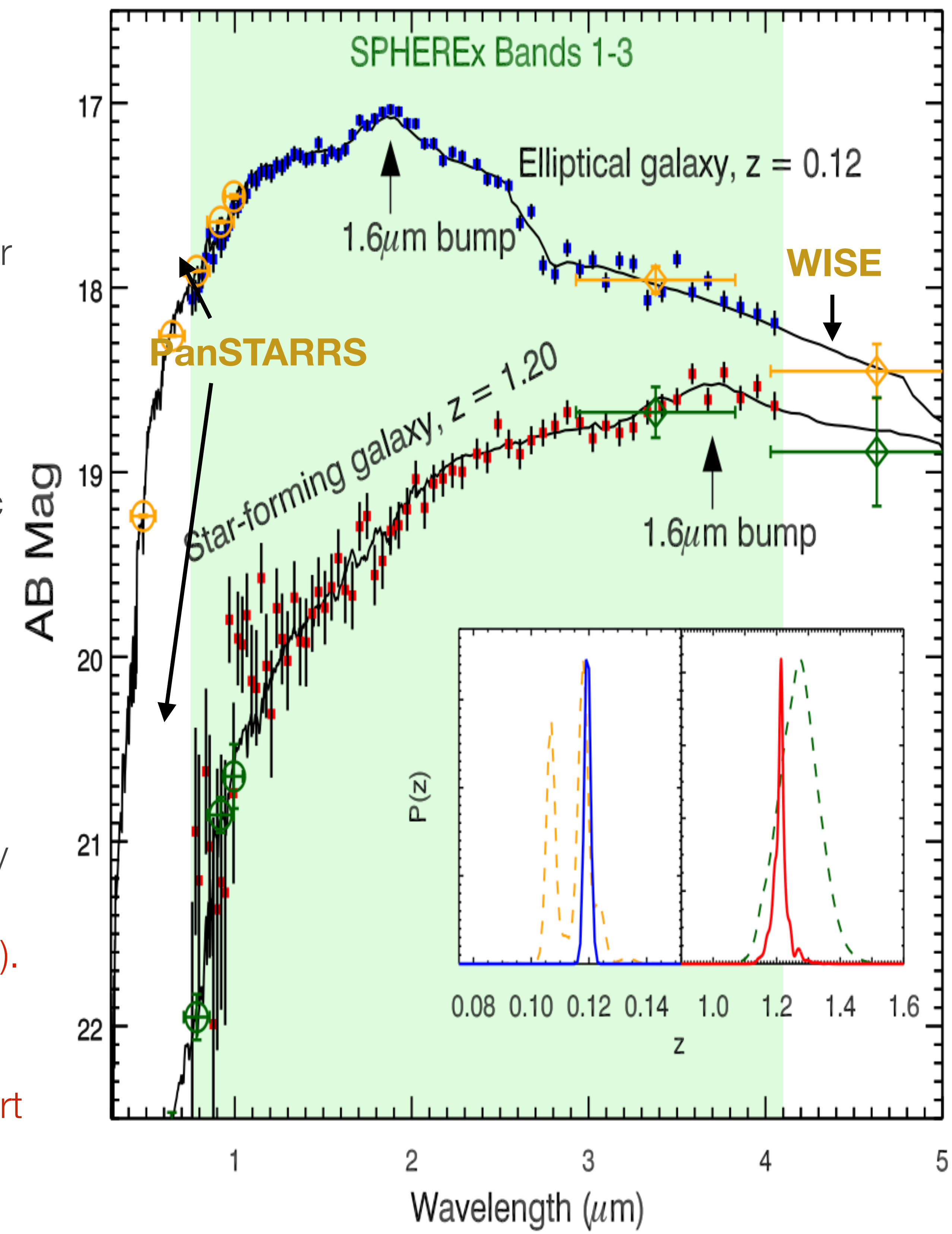


Dalal, O.D., Huterer, Shirokov 07

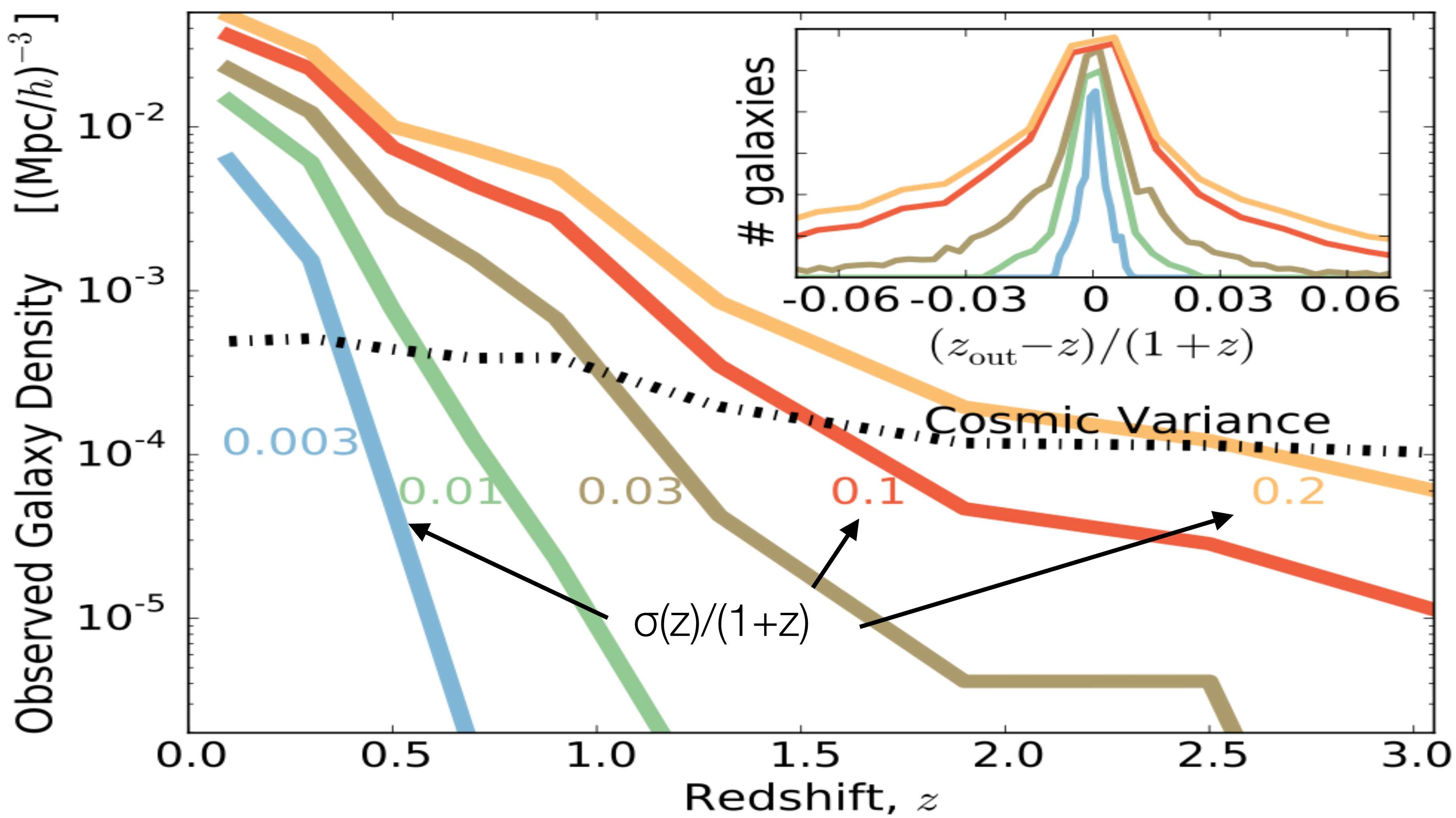
- The effect of primordial non-Gaussianity on galaxy clustering is most important on large scales
  - ➡ Full sky survey, low spectral resolution sample (de Putter & OD, 14).
- E.g., SDSS QSOs : $-49 < f_{NL}^{loc} < 31$ (95% C.L., Leistedt & Peiris 13)

Building a 3-D Galaxy Catalog with SPHEREx

- From our full-sky 97 bands, we extract the spectra of known sources using the full-sky catalogs from PanSTARRS/DES and WISE.
  - ➡ Blending and confusion are easily controlled.
- We compare this spectra to a template library (robust for low redshift sources):
  - ➡ For each galaxy, redshift but also other properties (stellar mass, dust content…).
- The 1.6 μm bump is a well known universal photometric redshift indicator (e.g., Simpson & Eisenhardt 99).
- We simulated this process extensively using the COSMOS data-set using the same process as Euclid/WFIRST (Capak et al.).
- A spectra is obtained for any type of galaxy and not only ELGs:
  - ➡ Ideal for multi-tracer studies (McDonald & Seljak 09).
- The power of low-resolution spectroscopy has been demonstrated with PRIMUS (Cool++14), COSMOS (Ilbert ++09), NMBS (van Dokkum++09).



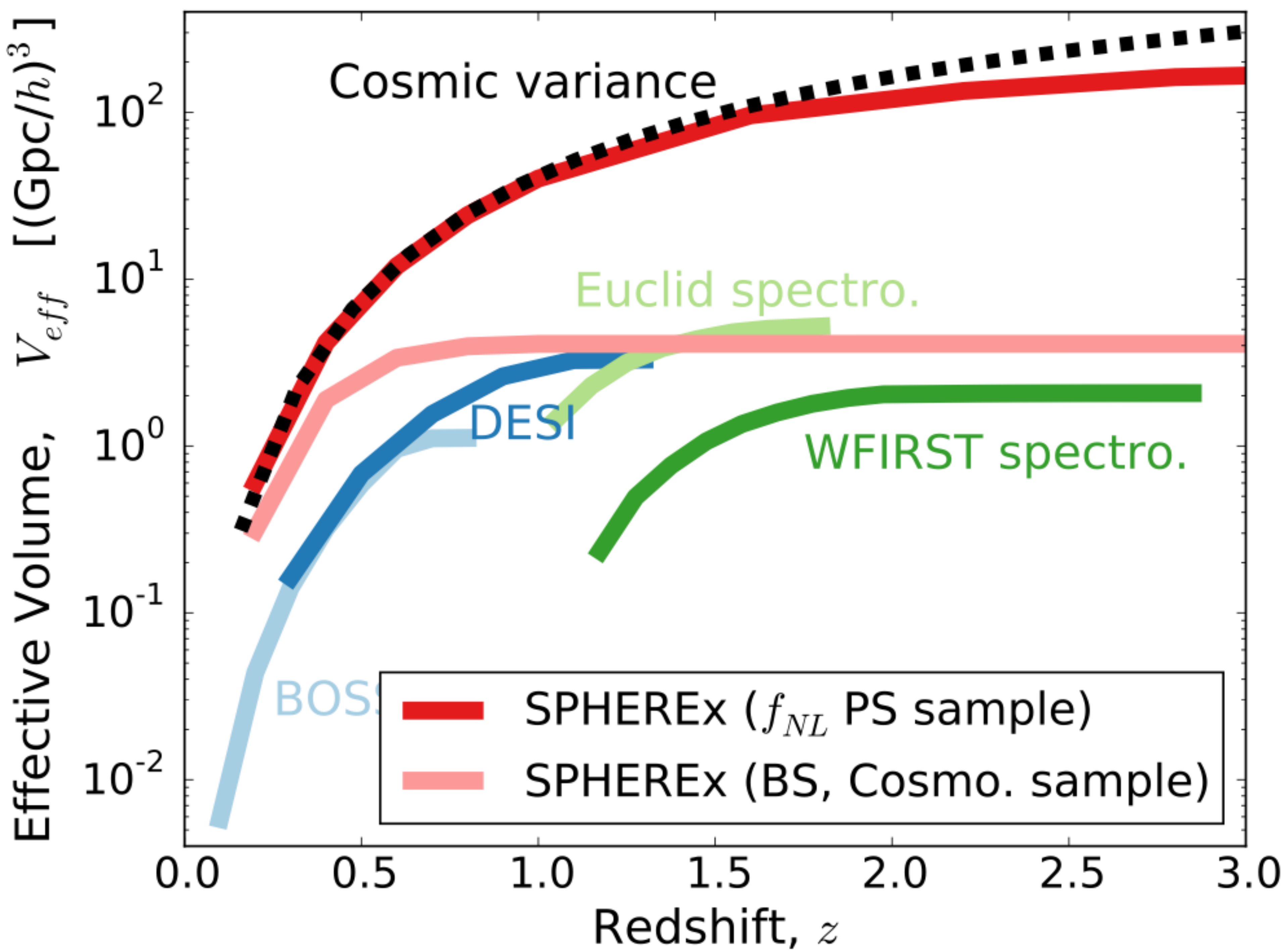
SPHEREx All-Sky Galaxy Density



- Full source extraction and redshit measurement pipeline (Capak & Masters).
- Detect 1.4 billions sources:
  - ➡ 301M of which with 10% z accuracy, 120M with 3% and 9.8M 0.3%.
- Spectra of all types of galaxies, i.e., not only emission line galaxies:
  - ➡ Ideally suited for multi-tracer studies.
- The high σ(z) sample drives the power-spectrum f_{NL} constraints while the lower σ(z) sample drive the bispectrum and other cosmological parameter constraints.

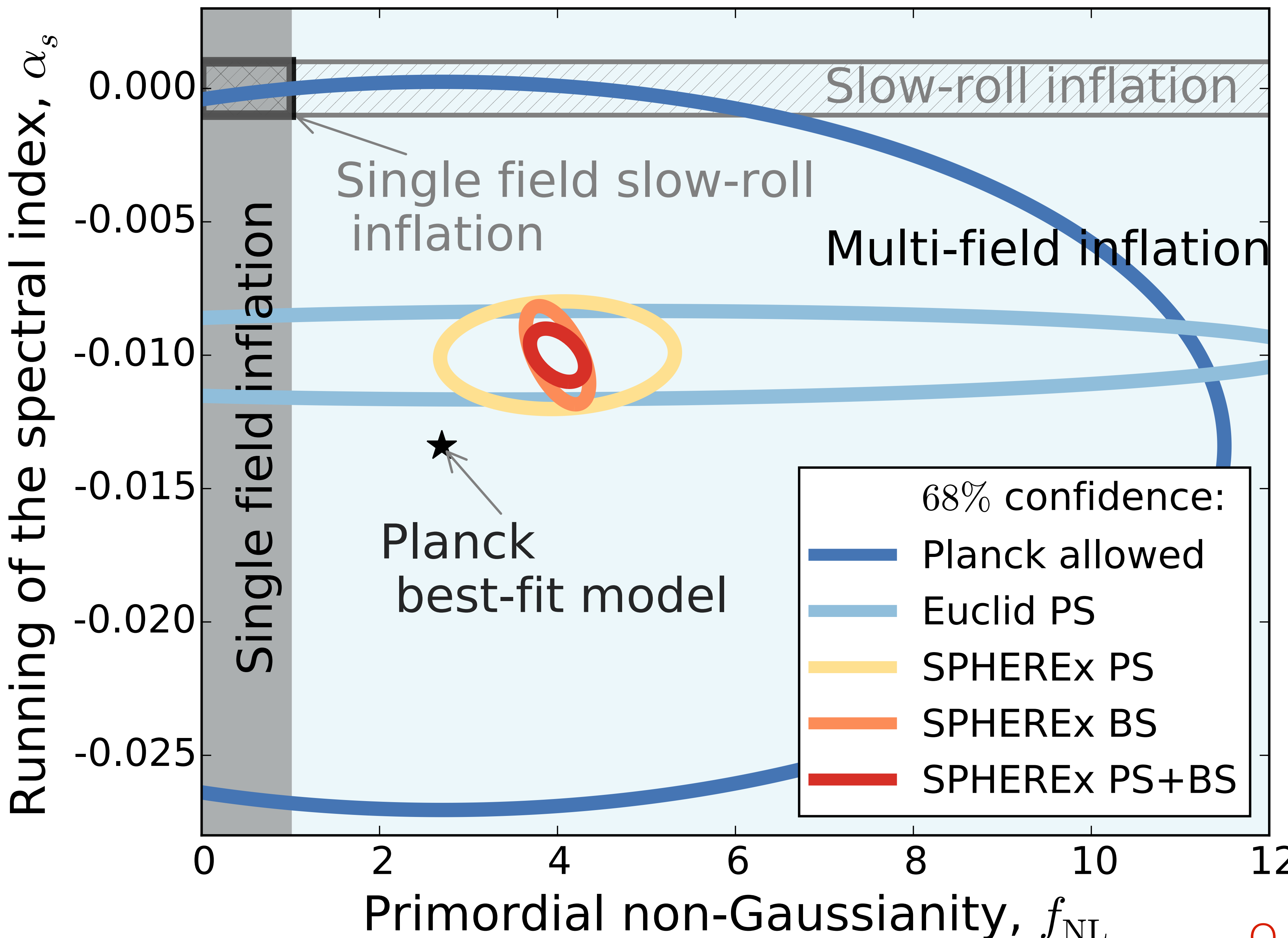
SPHEREx Probes a Large Effective Volume

$$V_{eff} = V_{survey}\sqrt{\frac{P_{gal}}{P_{gal} + \frac{1}{n_{gal}}}}$$



SPHEREx as a Probe of non-Gaussianity

$\sigma(f_{NL}^{loc}) \sim 0.8$ (3-D Power-spectrum)
$\sigma(f_{NL}^{loc}) \sim 0.2$ (3-D Bispectrum)



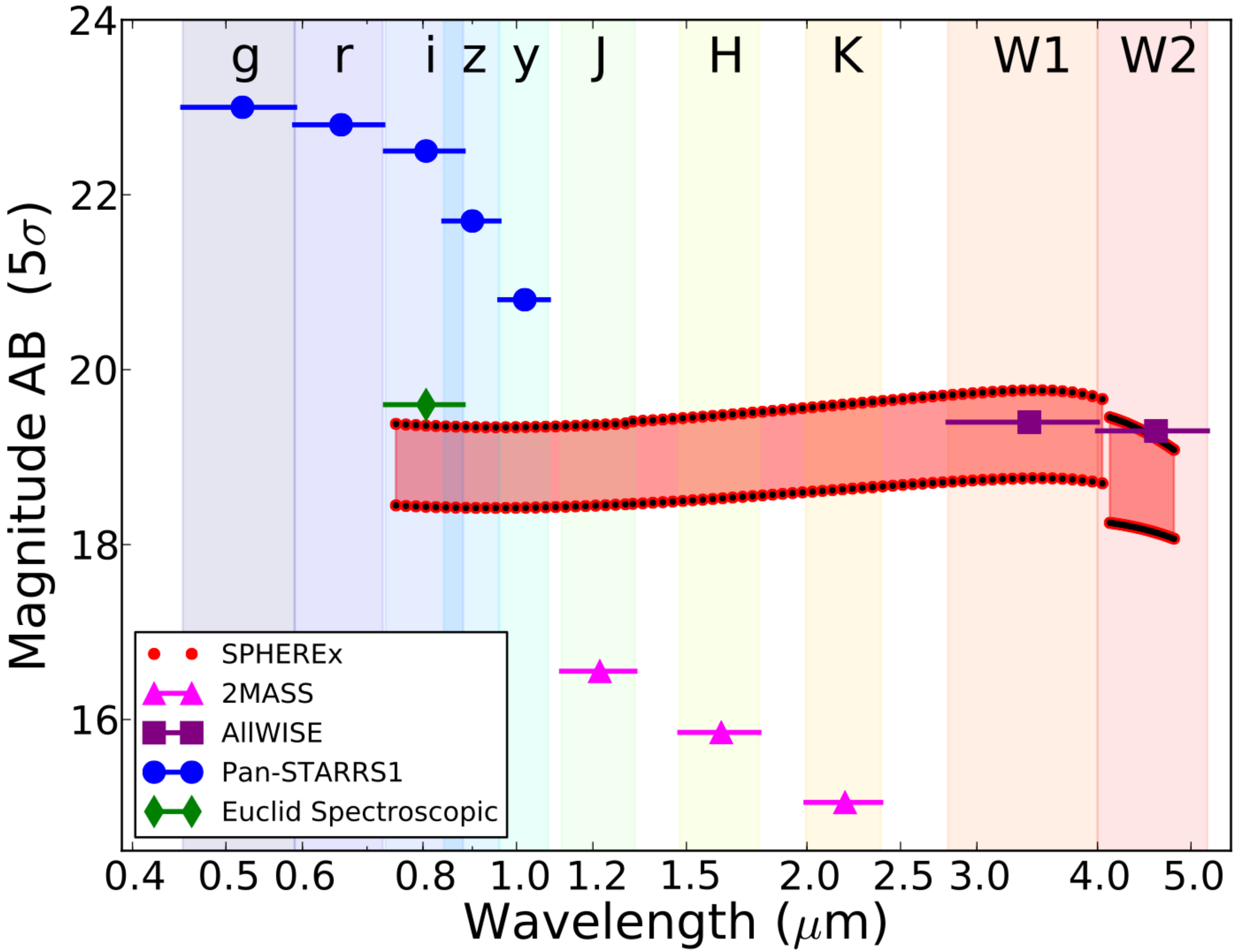
O.D., Bock et al. 2014
Alvarez et al. 2014

SPHEREx Cosmological Parameters Constraints

1σ errors	PS	Bispec	PS + Bispec	EUCLID (GC)	Current
$f_{\rm NL}^{\rm loc}$	0.87	0.23	0.20	5.59	5.8
Tilt n_s $(\times 10^{-3})$	2.7	2.3	2.2	2.6	5.4
Running α_s $(\times 10^{-3})$	1.3	1.2	0.65	1.1	17
Curvature Ω_K $(\times 10^{-4})$	9.8	NC	6.6	7.0	66
Dark Energy FoM $= 1/\sqrt{\rm DetCov}$	202	NC	NC	309	25

Assuming Planck prior

SPHEREx All-Sky Survey Depth



A Very Rich Legacy Catalog

Detected galaxies	1.4 billion	Properties of distant and heavily obscured galaxies	Simulation based on COSMOS and Pan-STARRS
Galaxies with $\sigma(z)/(1+z) < 0.1$	301 million	Study large scale clustering of galaxies	Simulation based on COSMOS and Pan-STARRS
Galaxies with $\sigma(z)/(1+z) < 0.03$	120 million	Study (Hα, Hβ, CO, OII, OIII, SII, H_2O) line and PAH emission by galaxy type. Explore galaxy and AGN life cycle	Simulation based on COSMOS and Pan-STARRS
Galaxies with $\sigma(z)/(1+z) < 0.003$	9.8 million	Cross check of Euclid photo-z. Measure dynamics of groups and map filaments. Cosmological galaxy clustering, BAO, RSD.	Simulation based on COSMOS and Pan-STARRS
QSOs	> 1.5 million	Understand QSO lifecycle, environment, and taxonomy	Ross et al. [81] plus simulations
QSOs at $z > 7$	1-300	Determine if early QSOs exist. Follow-up spectroscopy probes EOR through Lyα forest	Ross et al. [81] plus simulations
Clusters with ≥ 5 members	25,000	Redshifts for all eRosita clusters. Viral masses and merger dynamics	Geach et al. [82]

And Much More…

Main sequence stars	> 100 million	Test uniformity of stellar mass function within our Galaxy as input to extragalactic studies	2MASS catalogs
Mass-losing, dust forming stars	Over 10,000 of all types	Spectra of M supergiants, OH/IR stars, Carbon stars. Stellar atmospheres, dust return rates, and composition of dust	Astro-physical Quantities, 4th edition [ed. A.Cox] p. 527
Brown dwarfs	>400, incl. >40 of types T and Y	Atmospheric structure and composition; search for hazes. Informs studies of giant exoplanets	dwarfarchives.org and J.D. Kirkpatrick, priv. comm.
Stars with hot dust	>1000	Discover rare dust clouds produced by cataclysmic events like the collision which produced the Earths moon	Kennedy & Wyatt (2013)
Diffuse ISM	Map of the Galactic plane	Study diffuse emission from interstellar clouds and nebulae; hydro-carbon emission in the 3μm region	GLIMPSE survey (Churchwell et al. 2009)

- We are organizing a community workshop on the new astrophysics enabled by SPHEREx
  - ➡ Feb. 24-26 @ Caltech, Pasadena
  - ➡ http://spherex.caltech.edu/Workshop.html

SPHEREx and Other Surveys

- SPHEREx maps the full sky:
  - ➡ SPHEREx overlaps with your survey!
- SPHEREx has strong scientific synergies with other ground or space based surveys:
  - ➡ SPHEREx maps the low redshift universe whereas Euclid and WFIRST spectroscopic surveys target z>1.
  - ➡ E.g., substantially increase the SNR for galaxy-galaxy lensing if using in conjunction with deep imagers such as LSST, Euclid and WFIRST.
  - ➡ By mapping exquisitely the low-z universe, SPHEREx will help mitigate the intrinsic alignment systematic for WL (e.g., Eifler++15).
  - ➡ SPHEREx will substantially help with photometric redshift errors:
    - Direct redshift measurements for bright enough sources.
    - Help reduce catastrophic failures.
    - Ideal for clustering redshift analysis (e.g., Newman++08, Ménard++13)
    - Stacking analysis might be very powerful for faint sources (study in progress w/ M. White et al.).
  - ➡ SPHEREx will help measuring cluster redshift over the full sky (study in progress).

SPHEREx Enables a Strong Control of Systematics

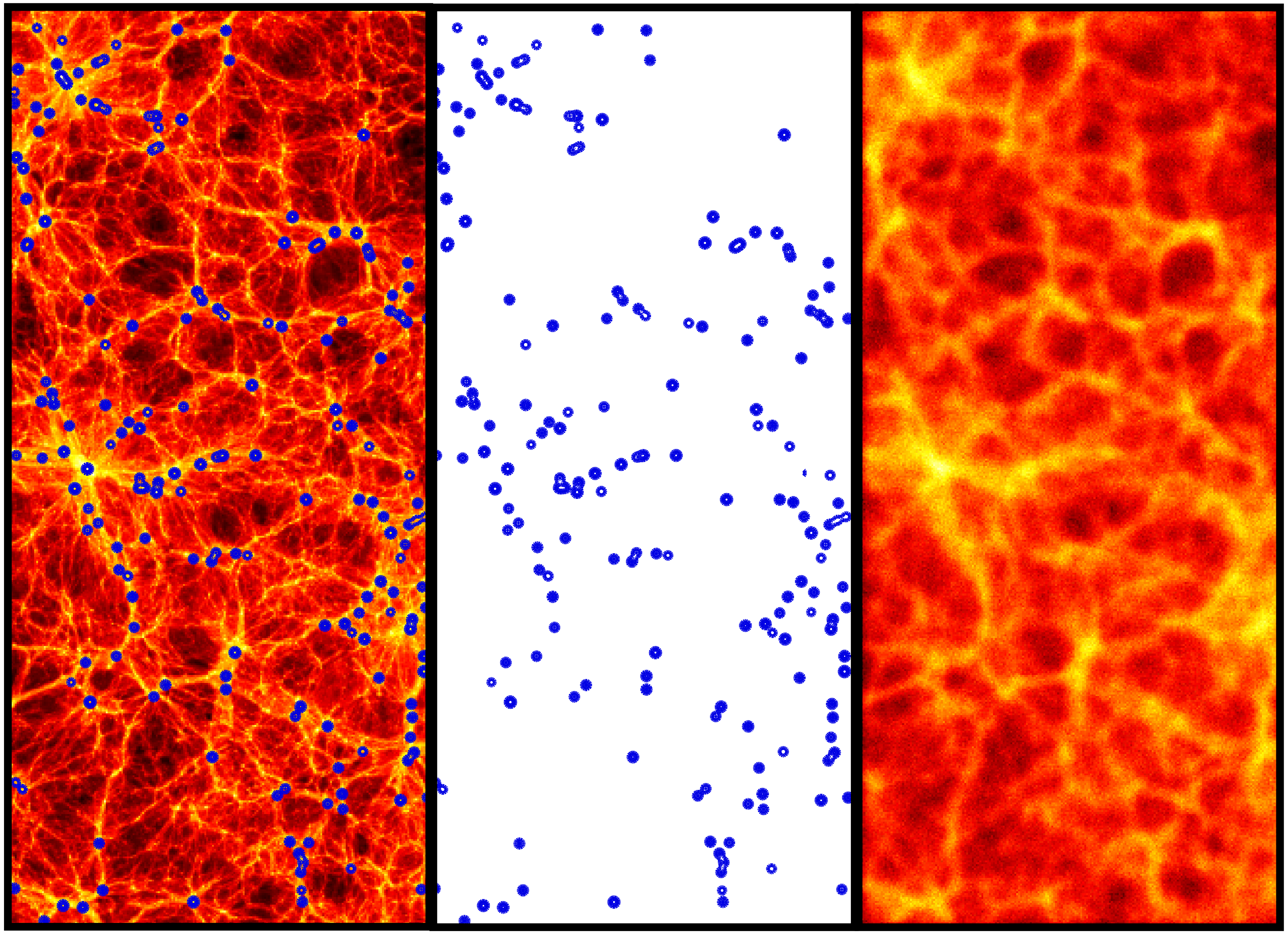
- Built in redundancy and long time stability guarantee a good control of systematics.
- In particular, the sources of error coherent on large angular scales (~ 10 deg.), which introduce artificial correlations in the 3-D source catalogs can be controlled:
  - ➡ We estimate all sources of error must be controlled to 0.2% (rms per dex in wavenumber, or 0.002 mag) to measure f_{NL}^{loc}=1.
  - ➡ We evaluate our systematic budget to be 0.160% rms per dex which gives us a margin of 75%.

Systematic	Mitigation	Amplitude	Conversion to $\delta n/n$	Technique	Coherent on large scales?	$\delta n/n$ % rms/dex
Galactic extinction	Observe in NIR, template projection	0.007 mag rms before mitigation	0.92/mag	e.g., Pullen & Hirata 2013	Yes	0.064
Noise selection non-uniformity	Inject simulated objects into real data	Template projection 0.2 mag rms (before mitigation)	1.8×10^{-3}/mag	e.g., Huff et al. 2014	Yes	0.036
Noise spectral z non-uniformity	Inject simulated objects into real data	Template projection 0.2 mag rms (before mitigation)	0.46/mag	e.g., Huff et al. 2014	Yes	0.092
Spectral gain errors	Measure flat field, calibrate on spectral standards	$\leq$ 0.25 % pixel-pixel gain	NA	Fixsen et al. 2000	No	NA
Source blending	High resolution Pan-STARRS/ DES/ WISE catalog	Negligible for bright sources	NA	Jouvel et al 2009	No	NA
PSF and Astrometry Error	Stack on 2mass catalogs	$\leq$ 0.1% flux	1	Zemcov et al. 2013	No	0.10
Cosmic Rays	Flag contaminated pixels	$\leq$ 1% pixels lost/exposure	NA	Russell et al. 2009	No	NA
Bright Sources	Mask persistent pixels	$\leq$ 2% pixels lost/exposure	1	Smith et al. 2008	Yes	0.04
Dark Current	Thermal stability	$\leq$ 10% of statistical error	NA	Zemcov et al. 2013	No	NA

O.D., Bock et al., arXiv:1412.4872

Galaxy Evolution Investigation

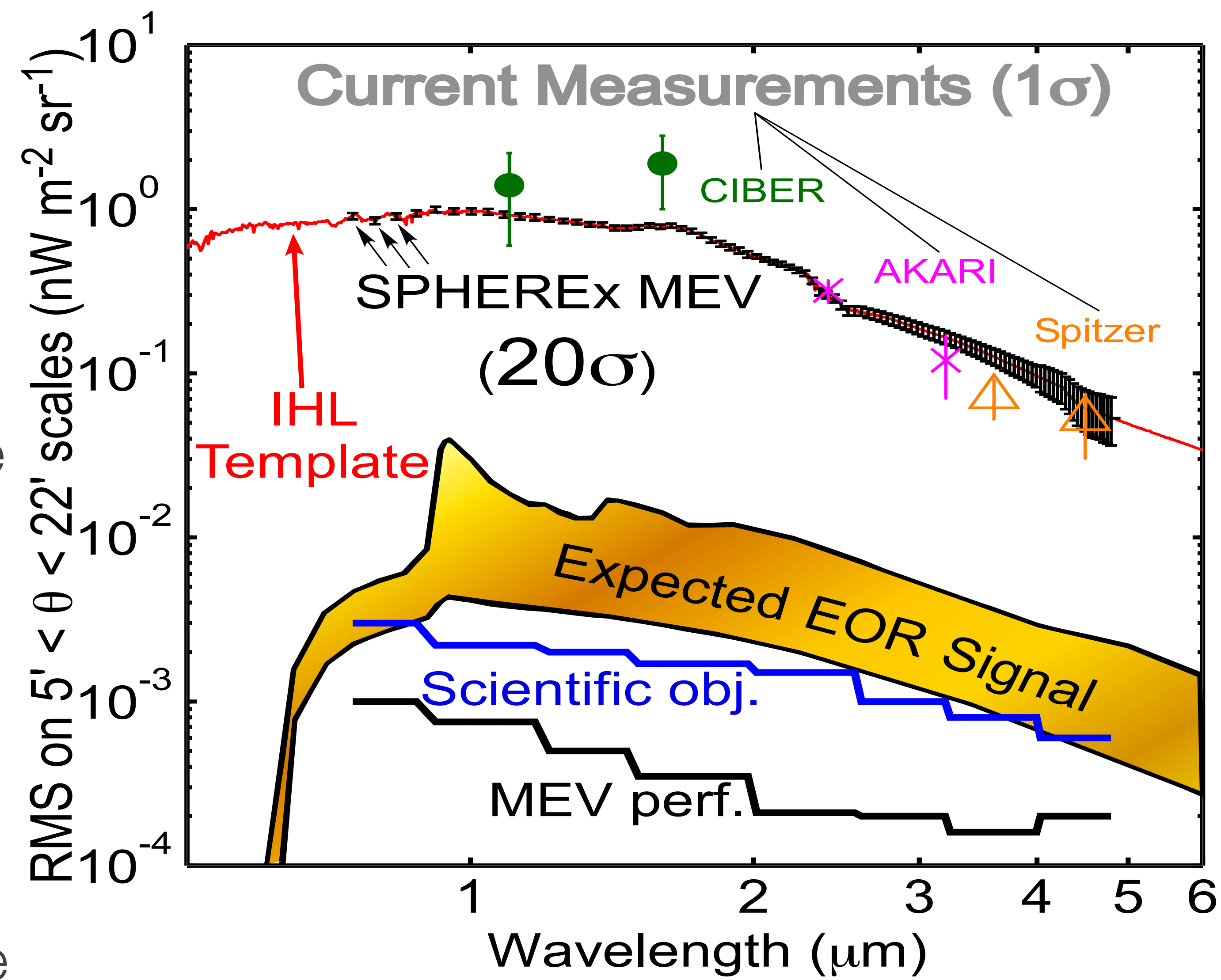
Astronomy in the Intensity Mapping Regime



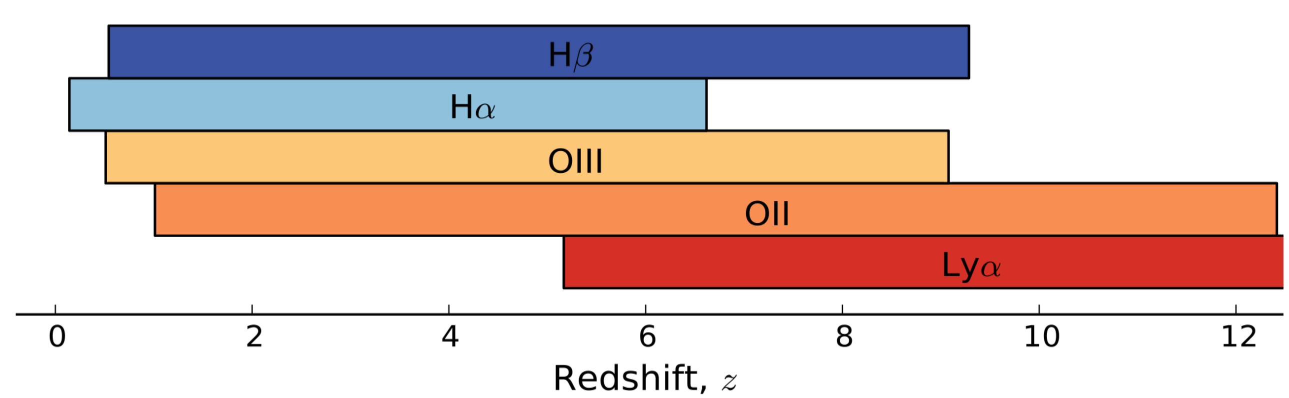
see also Tzu-Ching's and Hien's talks

Probing the Epoch of Reionization with SPHEREx

- SPHEREx orbits enable deep/frequent observations of the celestial poles (great for systematics!)
- SPHEREx wavelength coverage and resolution will enable large-scale measurement of spatial fluctuations in the Extragalactic Background Light (EBL).
- In particular, SPHEREx will monitor/ explain the Intra-Halo Light and its evolution (CIBER, Zemcov++14).
- SPHEREx has the raw sensitivity to probe the expected EOR signal (but separation with low z signal will be challenging).
- The sensitivity in this region will enable deep intensity mapping regimes using multiple lines at all redshift, and maybe Lyα at high redshift (see Croft++15)

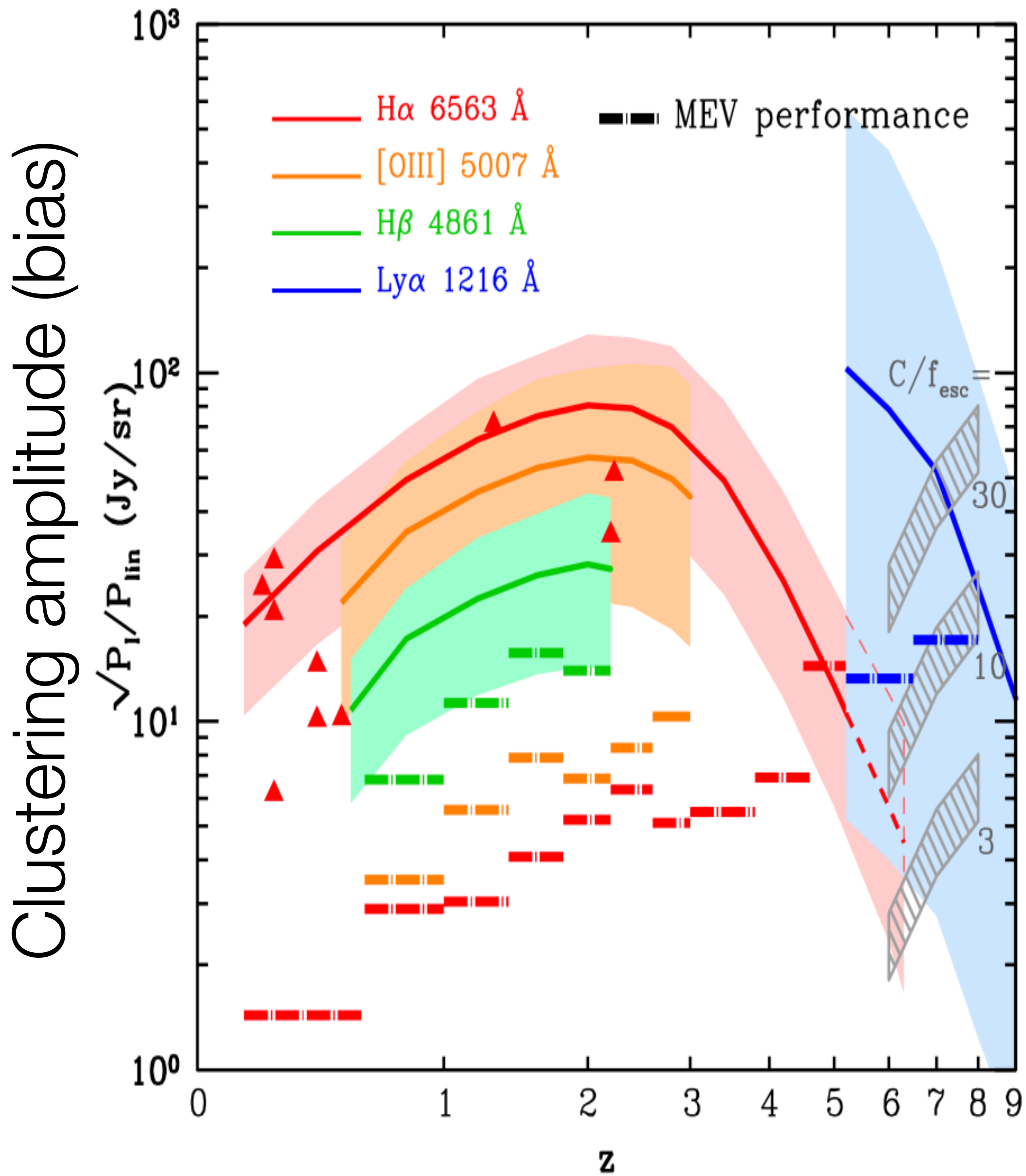


Redshift coverage of SPHEREx measured emission lines:



Intensity Mapping 3D Clustering with SPHEREx

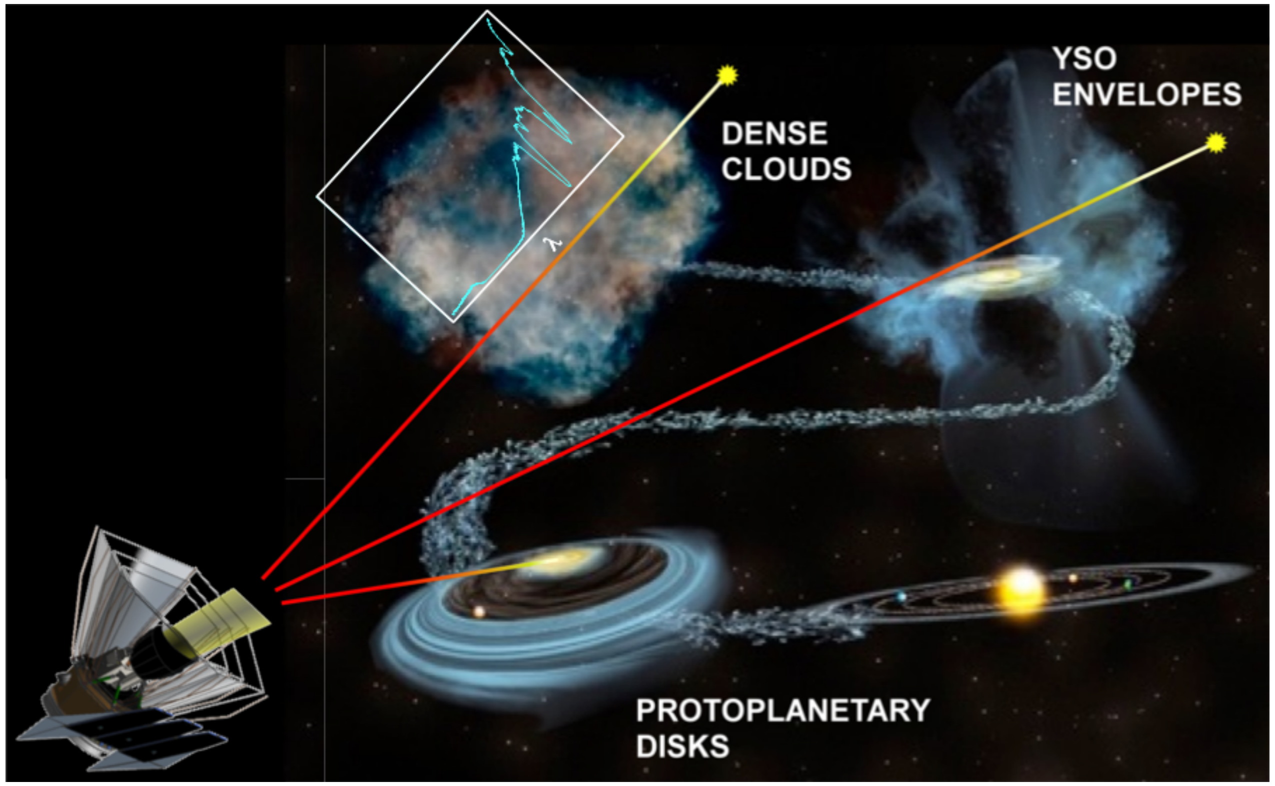
- SPHEREx will measure with high SNR the <u>*line luminosity weighted bias*</u> at multiple redshifts with multiple emission lines.
- This bias is directly proportional to the total light production at at a given time and thus proportional to the SFR.
- SPHEREx will map SFR throughout cosmic times, when it increases, peaks and declines.
- SPHEREx <u>*might*</u> have sensitivity to detect Lyα from EOR.



Ice Investigation

SPHEREx Galactic Ice Investigation

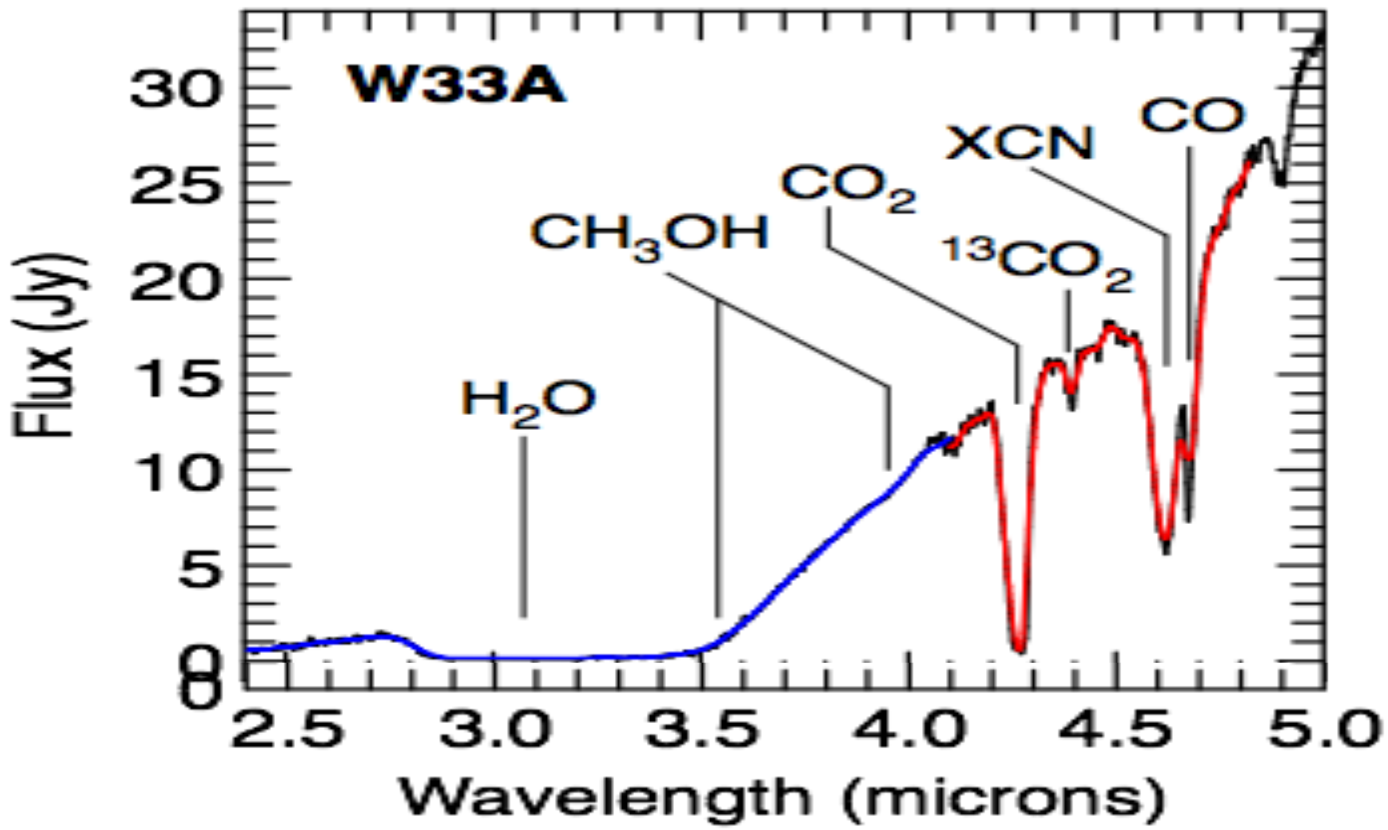
- Gas and dust within dense molecular clouds are the reservoirs from which stars and planets assemble:
  - ➡ Within molecular clouds, H_2O ice abundance is $10^2 - 10^3$ x greater than H_2O gas.
  - ➡ In young protoplanetary disks, both models and the limited data presently available suggest that substantial amounts of water and, perhaps other biogenic molecules, exist primarily in ice toward the disk mid-plane and beyond the snow line.



- Point sources will be used as background targets for absorption spectroscopy:
  - ➡ WISE has catalogued > 10^6 (non-confused) galactic sources at 3.4 μm and 4.6 μm with evidence for extinction due to intervening gas and dust.
  - ➡ SPHEREx will measure their spectra with a SNR > 100 per $\Delta\lambda$.

O.D., Bock et al. 2014

SPHEREx Galactic Ice Investigation



ISO spectra

- SPHEREx will be a game changer in our efforts to resolve long-standing questions about the amount and evolution of key biogenic molecules (H_2O, CO, CO_2, and CH_3OH) through all phases of star and planet formation by:
  - ➡ Increasing the number of ice absorption spectra by > 1000-fold.
  - ➡ Observing in a spectral region rich in ice features of several key species.
  - ➡ Spectral resolution high enough to isolate absorption due to each species; pixels small enough to avoid confusion; high SNR.

- SPHEREx will "trace the history of organic molecules through their cycles of formation, often on the surfaces of dust grains, within molecular clouds to their incorporation in planetary systems." [NWNH]

Conclusions: Ready for Phase A!

- SPHEREx has been proposed in Dec.14 as a SMEX mission and selected for Phase-A study in August 15.

- SPHEREx will create the first all sky near-infrared spectroscopic survey:
  - ➡ SPHEREx will create a dataset of lasting legacy.

- SPHEREx offers a simple and very robust design and modus operandi:
  - ➡ It naturally enables a high control of systematics thanks to multiple built-in redundancy.

- SPHEREx key cosmology goals are complementary to CMB based constraints:
  - ➡ It allows to probe non-Gaussianity better than any planned experiment (x5 better than Planck/Euclid using the power spectrum and x10 using the bispectrum).
  - ➡ It is sensitive enough to probe regions of well defined theoretical interests.

- SPHEREx is complementary to and has strong synergies with Euclid and WFIRST:
  - ➡ It probes the $z<1$ Universe while Euclid and WFIRST galaxy clustering studies focus on the higher z Universe.
  - ➡ SPHEREx will facilitate the control of systematics for Euclid and WFIRST (e.g., photo-*z*, intrinsic alignment,…) while enabling new scientific opportunities (e.g., exquisite galaxy-galaxy lensing, magnification, …).

- SPHEREx will also enable other original and powerful studies:
  - ➡ The extra-galactic background light from $z=0$ till the reionization era.
  - ➡ The origin of water and biogenic ices in young stellar objects and protoplanetary systems.

- Community support is important!
  - ➡ If you like SPHEREx, please mention it in your papers or talks.

http://spherex.caltech.edu

FIN